Energy Economics 71 (2018) 332–343

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Climatic impacts on energy consumption: Intensive and extensive margins

Jianglong Li [a], Lisha Yang [b,*], Houyin Long [c]

[a] School of Economics and Finance, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, PR China
[b] Institute of Economic Development and Reform, Huaqiao University, Xiamen, Fujian 361021, PR China
[c] School of Economics and Management, Ningde Normal University, Ningde, Fujian 352100, PR China

ARTICLE INFO

Article history:
Received 30 May 2017
Received in revised form 12 January 2018
Accepted 7 March 2018
Available online 12 March 2018

JEL classification:
C23
D12
Q01
Q41
Q56
R11

Keywords:
Climatic impacts
Energy consumption
Residential sector
Intensive margin
Extensive margin

ABSTRACT

Contrary to "greenhouse effect", climate change might in turn impact energy consumption due to its influences on usage pattern and purchasing decisions for heating and cooling appliances, which are defined as intensive and extensive margins respectively in literature. As the largest energy consumer and carbon dioxide (CO_2) emitter worldwide, China has already raised great concerns for its energy consumption and the potential effect on global warming. However, the reverse impacts of climate change on China's energy consumption are still unanswered. This paper tries to fill the research gap by conducting the first estimates about the climatic impacts on residential energy consumption in China, including both intensive and extensive margins. Random and exogenous temperature shocks are used to identify the effects of climatic change on households' electricity consumption and air conditioner adoption. Differences of responses by season and by climate zone are particularly explored, especially considering the possible effect of government-provided central heating system in North China during wintertime. We find that hotter summer would result in larger impact than colder winter, implying increased electricity consumption in the whole year from global warming. Furthermore, intensive margin dominates in summer while its role is only minor in winter. We also find that there are substantial differences by climate zone in responses of electricity consumption and air conditioner adoption, potentially due to central heating system and different tolerance to temperature. The findings can help us make informed decisions on planning future energy/electricity development, as well as climate and energy policies. We also anticipate our paper to provide knowledge and broader implications directed toward alleviating global climate warming.

1. Introduction

The climate is a key element that matters for the sustainable human life, and there is a growing concern on the impacts of climate change (Deschênes and Greenstone, 2011). On contrary to the "greenhouse effect", different climates would in return change energy consumption (and thus the energy-related CO_2 emissions) by changing human's behaviors. Compared with wind speed and humidity, temperature stands out among the climatologic factors that affect energy consumption, as reported by Deschênes and Greenstone (2011), Fikru and Gautier (2015). According to Hekkenberg et al. (2009a), the impacts of temperature on energy consumption are mainly achieved through several mechanisms. The first one is that people tend to buy more heating/cooling appliances in a colder winter or in a hotter summer. Second, a larger temperature difference needs to be overcome, thus increasing the heating/cooling load. Finally and more straightforwardly, people are more inclined to turn on heating/cooling appliances on cold/hot days than on warm/cool days. In literature, the first mechanism is usually named as "extensive effect" because it changes the purchasing decisions of appliances, while the second and third mechanisms are referred as "intensive effect" because they increase energy consumption given the quantity of heating/cooling appliances. In this paper, referring to previous studies especially Auffhammer (2014), Auffhammer and Mansur (2014) and Davis and Gertler (2015), the intensive margin is formally defined as how energy consumption responds to temperature change given current equipment stocks, i.e., households operate installed equipment more frequently. The extensive margin measures how climatic factors drive households' adoption decisions, i.e., households install additional heating/cooling appliances.

Residential sector is the only sector whose energy consumption is directly related to an individual household's decisions (Bin and Dowlatabadi, 2005), therefore, it might be the only sector whose energy consumption is heavily affected by climate, especially by temperature. Furthermore, residential sector is one of the main consumers of energy in most countries. On average worldwide, energy consumption in residential sector accounts for about 30% of global energy consumption. On the contrary, the other three sectors that also significantly contribute to energy consumption, including transportation, industry and commerce, are much less temperature dependent (Salari and Javid, 2016).

* Corresponding author.
E-mail address: yangls@hqu.edu.cn (L. Yang).

https://doi.org/10.1016/j.eneco.2018.03.010
0140-9883/

Energy used in the residential sector mostly goes toward heating/cooling residential buildings (Javid et al., 2014), while the heating/cooling process is dependent on human's choice of using and adopting heating/cooling appliances, especially air conditioners.[1] For example, a hotter summer might induce more people to use more and/or adopt more air conditioners. Then, how to depict and model households' behavior response to temperature change? As pointed out by Auffhammer and Mansur (2014), an ideal dataset would provide information on the energy consumption difference when households are randomly relocated to a new climate, given all else equal. Unfortunately, this perfect experiment is not feasible. Thus, an alternative approach used by economists is to examine the cross-sectional variation in climate. Specifically, if there are two seemingly identical households living in different climate zones, one can then observe the differences of their energy uses and analyze whether these differences are correlated with climate variation.

Therefore, China is an ideal setting for this study because of its varied climate. China is the third largest country with territory of 9.6 million km^2. The climate zones range from tropic to subarctic, and from ocean climate (coastal areas in the east) to desert climate (inland areas in the west). The populated areas locate from sea level up to >4000 m (Tibetan Plateau). The climate varies substantially across different regions of China (as shown in Fig. 1), providing substantial variation that enables better understanding of people's responses to weather. The main concern with the cross-sectional approach is that omitted variables might lead to biased estimation: unobservable differences across regions may be correlated with climate. For example, Albouy et al. (2016) find households living in northern regions tend to be less heat-tolerant than southern households. Thus, the third approach is to use panel data-based model which can control for unobservable differences. In order to identify the variation in temperature and unobservable heterogeneities, we employ monthly data at China's provincial level so that both spatial and temporal climatic differences can be captured.

This study is complicated by the non-linear pattern of energy consumption in response to climate change. In winter, the relationship between energy consumption and temperature is negative because an increase in temperature diminishes the demand for energy used for heating purposes. In contrast, in summer, a temperature increase may stimulate energy consumption since an increase in temperature results in a higher use of air conditioners and other cooling devices. It requires a specific treatment in order to take this non-linearity into account (Bessec and Fouquau, 2008).

Another interesting question is how the climatic impacts on energy consumption differ by climate zone. This is particularly important for China except for its large territory. In China, government-provided central heating is limited to the area that belongs to the north of a line from the Qinling Mountains to the Huaihe River ("Qin-Huai line" in brief). This dividing line, which was established by government officials sixty years ago, bisects China into areas have and have not central heating system in wintertime. In the north area of Qin-Huai line, households in winter do not need to change their private energy consumption behaviors as a response to temperature change, because central heating system would maintain a comfortable indoor temperature. Thus, people in the north do not have to consume more energy or purchase more heating appliances even in a colder winter. Contrarily, in the south area of Qin-Huai line, residential energy consumption might respond to temperature through intensive or extensive adjustments.

Thus, evidences on energy consumption in residential sector have important implications for economic, resource and environmental consequence, as well as enable policy makers to take informed decisions on energy and environmental policies. The objective of this paper is to expand the previous studies by identifying the intensive and extensive margins using a single framework, and to explore how seasonal and regions (divided by Qin-Huai line) influence energy consumption and air conditioner adoption in China. Conducting the study specific to China has broader implications worldwide. Due to differences in household income and demography, the climatic impacts might be quite different by country/region (McNeil and Letschert, 2008). Rational climate and energy policies require knowledge on how households around the world would adjust their behaviors as the responses to climate change (Burgess et al., 2017). Thus, the empirical studies should explore the likely responses of households to climatic change in different countries, especially China who is the most populous countries and second largest economy.

Study for the climatic impact on energy consumption is important at both theoretical and policy levels. The main energy type consumed by households is electricity, thus the link between temperature and energy consumption can be applied to project capacity requirements of the energy sector, fuel use in electricity generation, space heating and cooling needs by final consumers, as well as energy-related emissions (Fazeli et al., 2016). Also, the patterns of temperature dependence are important for assessing future electricity demand, especially in the context of global warming (Gupta, 2012). In the long-term, higher (lower) temperatures, especially uncomfortable high (low) temperatures, may alter the purchasing decisions of air conditioners and other heating/cooling appliances (Sailor and Pavlova, 2003; Davis and Gertler, 2015). In this regard, higher (lower) temperatures in summer (winter) may be a driver for a social-economic trend which has a lasting impact on future electricity demand. Seasonally, temperature dependence may lead to an increasing importance of summer and winter months in electricity load. It may have important implications for capacity deploying of electricity generation, maintenance scheduling as well as demand-side management.

In this paper, we make three contributions to empirical literature. First, we conduct the empirical analysis using panel data across provinces of China. China is the largest energy consumer and the most populous country in the world. Its energy demand in residential sector is increasing rapidly. Understanding how people responds to climatic change is crucially important. Second, much attention is paid to identify intensive and extensive margins. Thus, we could describe how energy consumption change with temperature given current levels of air conditioners, and how temperature drives the adoption decisions of air conditioners. To the best of our knowledge, the study for China concerning climate impacts in intensive and extensive margins is still rather sparse. Third, of particular interest is that we explore how intensive and extensive margins differ by climate zones within China and by season, especially considering government-provided central heating system in winter of North China.

The remainder of the paper is organized as follows. In Section 2, we give a brief review about the climatic impacts on energy consumption. Section 3 describes the model specification and dataset. Section 4 reports and analyzes the empirical findings. Section 5 details further discussion about climatic impacts in different climate zones. In Section 6, we present the main conclusions and the related implications.

2. Literature review: understanding climatic impacts on energy consumption

How the climate affects society and the economy is a challenging question that needs to be answered. In recent years, numerous studies have emerged to address this issue. Auffhammer et al. (2013) provide a detailed discussion of weather data, climate models, and their use in the social sciences. Hsiang (2016) reviews and synthesizes recent advances in theoretical and empirical methods used to measure effects of climate on social and economic outcomes.

To be more specific to the issue of current paper, we are related to the previous studies concerning the climatic impacts on energy consumption, in particular the more recent studies relating the intensive

[1] Air conditioner gets a lot of attention within the analysis of energy economics and policies, both because of its high energy consumption and its disproportionate contribution to peak load (McNeil and Letschert, 2008).

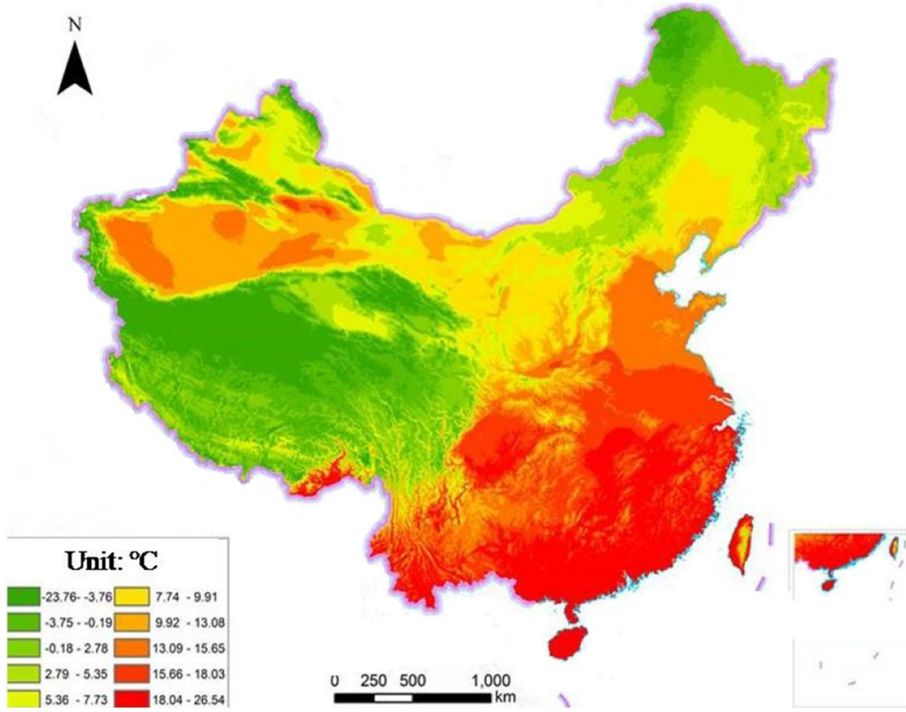


Fig. 1. The temperature distribution in China (year average in 2010)[a]. [a]http://www.baimao.com/export/factory/8579865.htm.

and extensive margins of climatic impacts. In literature, the energy-temperature relationship can be displayed as a hypothetical curve in Fig. 2. In the U-shaped curve, the minimum point is the threshold, measured by the balance temperature for heating and cooling (Gupta, 2012). Above the threshold, an increase in temperature would result in more cooling demand; while below the threshold, temperature decrease expects a higher heating demand. Socio-economic factors, such as residential income, affect the location and slope of energy-temperature curve (Hekkenberg et al., 2009b).

In literature, the temperature variable is usually quantified by the notion of heating degree days (HDD) and cooling degree days (CDD). Typically, HDD (CDD) is defined as the aggregate degrees below (above) the threshold over periods like a month[2] (Auffhammer and Mansur, 2014). This measurement has been widely used in many studies, including Considine (2000), de Dear and Brager (2001), Pardo et al. (2002), Cho et al. (2011), Fikru and Gautier (2015). Most of these related literature consider 65 °F (18.3 °C) as the threshold. However, the actual threshold should be specific to characteristics of buildings (such as insulation) and other non-temperature factors (Amato et al., 2005; Petrick et al., 2010; Fazeli et al., 2016). Therefore, recent studies have strived to find the appropriate thresholds of temperature. For example, Kaufmann et al. (2013) estimate the relationship between temperature and energy consumption in Massachusetts, and they propose that a set point of 65 °F biases statistical estimates for a warming climate. Considering the potential biases of exogenous thresholds, another strand of literature employs smooth transition regression (STR) model. Using STR model, the threshold points can be identified endogenously. Related studies can be seen in Moral-Carcedo and Vicens-Otero (2005), Bessec and Fouquau (2008), Lee and Chiu (2011), Gupta (2012).

Researchers also focus on the regional heterogeneities of the responses of energy consumption to climate impacts. Mansur et al. (2008) is an early comprehensive assessment of the different choice of fuels for consumers in warmer and colder locations. McNeil and Letschert (2008) conduct analysis of the relationship among CDD, air conditioner adoption, and electricity consumption by country/region. Auffhammer and Aroonruengsawat (2011) provide a panel data-based estimation on how the residential electricity consumption varies across climate zones. They use the complete billing data of California's three major investor-owned utilities during 2003 and 2006. According to the differences in climate conditions across the state, California is divided into 16 building climate zones. Deschênes and Greenstone (2011) also find that there is geographic heterogeneity in the responses of residential energy consumption to extreme temperatures.

Another strand of papers have paid attention to the relationship between energy consumption and temperature at different seasons. In summer and winter, the needs for cooling and heating would switch. The assumptions about the switch between cooling and heating and the related influences on energy consumption depend on technology and preferences, and therefore whether a linear model is suitable for

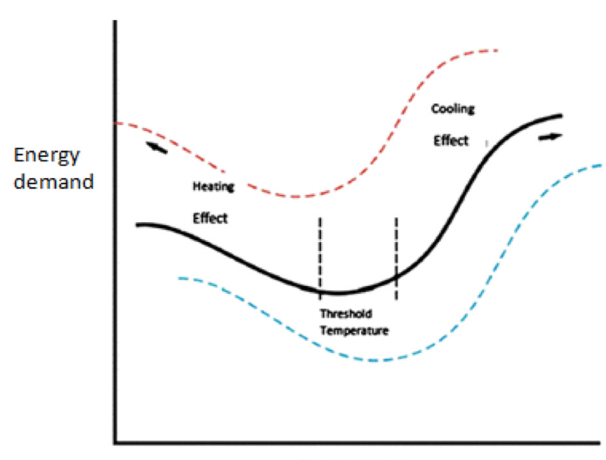


Fig. 2. The relationship between temperature and energy consumption. Sources: Adjusted from Gupta (2012).

[2] The thresholds can be different for HDD and CDD, allowing for a temperature interval within which electricity demand is irresponsive to temperature variations (Moral-Carcedo and Vicens-Otero, 2005).

estimating the energy consumption response over seasons should be empirically investigated (Henley and Peirson, 1997). Using a cubic polynomial, Franco and Sanstad (2008) find a nonlinear influence of average daily temperature on electricity consumption. Bessec and Fouquau (2008), Lee and Chiu (2011), De Cian et al. (2013) and Gupta (2012) all provide estimates of climate change's impacts on energy consumption at different seasons and using different models, including log-linear models, semi-parametric and non-parametric models.

Above all, most of existing literature focuses on how climate change affects energy consumption, showing that different temperatures outside call for changes in space heating and cooling needs. However, as stated by Auffhammer and Mansur (2014), the mechanism of how temperature affects heating and cooling process, and then its impact on energy consumption are still significantly less understood. For better understanding the climatic impacts on energy consumption, previous studies have made careful distinction between intensive and extensive margins. In the pioneering work of Dubin and McFadden (1984), they recognize that the demand for durables and their use are related decisions by the consumers. They derive a unified model of demand for durables and the derived demand for electricity. In recent studies, referring to the concept in international trade (Besedeš and Prusa, 2011), the intensive margin and extensive margin has been defined to separate households' response of usage pattern and adoption decisions for air conditioners (Auffhammer, 2014; Auffhammer and Mansur, 2014; Davis and Gertler, 2015). In theoretical, Auffhammer and Mansur (2014) propose a theoretical foundation for explaining why the utility maximizing households would change energy related expenditures in response to climate change, leading to the behavioral adjustments through intensive and extensive margins.

With regard to the intensive margin, several papers examine the short run response to temperature shocks (such as Asadoorian et al., 2008; Fikru and Gautier, 2015; Atalla et al., 2017). A common finding in these literature is that usage patterns of existing appliances, such as air conditioners, change in response to climate change. Over time, however, people will respond to climatic change along extensive margins (Davis and Gertler, 2015). They may change purchasing decisions of appliances, and even building characteristics (Auffhammer and Aroonruengsawat, 2011). In general, as Auffhammer (2014) points out, economists know less about these extensive margin adjustments than the intensive ones. There is only few literature examining the temperature and responses of air conditioner adoption (e.g. Sailor and Pavlova, 2003; Biddle, 2008; McNeil and Letschert, 2010; Auffhammer, 2014). In particular, Auffhammer (2014) explores China's temperature dependence of air conditioner adoption, which fills the research gap on extensive margin in the case of China. Davis and Gertler (2015) describe both how electricity consumption increases with temperature given current levels of air conditioners, and how climate and income drive air conditioners adoption decisions. Thus, this study provides a framework that investigates the intensive and extensive margins and applies it to study the issue in Mexico. Also, they find that the air conditioner adoption decisions in Mexico are tightly related to climate zones which are quite different between cold and warm municipalities.

According to the reviews for previous literature, one reason motivating us to pay particular attention to China is that the expected net impacts of climate change on its overall energy consumption and air conditioner adoption are ambiguous, and the related researches are far away from adequacy. For a country/region located in high latitudes such as Sweden, global warming might reduce its energy consumption and air conditioner adoption due to decreased heating requirements. On the contrary, for those who are located in low latitudes such as Singapore, global warming might have positive effects because of increased cooling requirements. However, the overall climatic impact on China is unclear because its territory distributes from tropic to subarctic, and few studies exist yet of climatic impacts in the case of China.

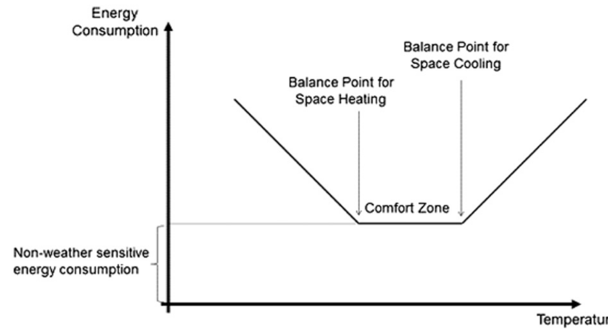


Fig. 3. Linear model with a comfort zone for the relationship between temperature and energy consumption.
Sources: Fazeli et al. (2016).

3. Methodology

The first question we face is how to measure climatic change. In the linear symmetric models, it is assumed that there is an instant shift from heating equipment to cooling devices for infinitesimal deviations from the balance point temperature. This assumption is not realistic (Fazeli et al., 2016). A temperature interval should be allowed, within which electricity consumption does not respond to temperature variations (Moral-Carcedo and Vicens-Otero, 2005). Consequently, several studies have attempted to refine the linear V-shaped models by allowing for a *comfort zone*, within which no heating or cooling is required to keep the indoor temperature at the required level (such as Hekkenberg et al., 2009b; Fikru and Gautier, 2015). The energy temperature relationship with a comfort zone is shown in Fig. 3.

We focus our analysis on winter and summer because most of Chinese people use heating and cooling appliances only in the two seasons. How to set reasonable thresholds for comfort zone? In Song et al. (2017), they find that in Tianjin city of China in 2016, the most common trigger temperature for air conditioning is 28.4 °C (for cooling) and 19.7 °C (for heating). In Wu et al. (2015), they use a nationwide thermal comfort survey data supported by the Ministry of Housing and Urban-Rural Development of China, and find that the comfort zone ranges between 18 °C and 27 °C, with its unsatisfied rates below 10% and satisfaction rates above 45%. The survey data used in Wu et al. (2015) might be representative and convincing because it involves 28,000 samples and covers different climate zone in China. We thus adopt the results in Wu et al. (2015) as the benchmark of thresholds, ranging between 18 °C and 27 °C.[3] The temperature deviation is then defined as follows:

$$TDEV_{ijt} = \begin{cases} -1 \times \min\left(0 temp_{ijt} - 18\right) & if \quad j \in \{Dec, Jan, Feb\} \\ \max\left(0 temp_{ijt} - 27\right) & if \quad j \in \{Jun, Jul, Aug\} \end{cases} \tag{1}$$

where $TDEV_{ijt}$ denotes the deviation of temperature from comfort zone in province i, month j and year t. Eq. (1) indicates that only when temperature is lower than 18 °C in winter or is higher than 27 °C in summer, temperature change would influence the usage pattern or purchasing decisions of households. In winter, with the declining of temperature, people would purchase more heating appliances or the existing heating appliances would be used more frequently. Thus, *TDEV* in winter is defined as the opposite of deviation of temperature from 18 °C. When temperature ranges from 18 °C~27 °C, *TDEV* is constantly equal to zero because electricity consumption is irresponsive to temperature

[3] In the previous version of this paper, we use 10 °C and 20 °C as the thresholds under no specific reason. The regression results is generally similar to this version. We thank the reviewer for pointing out the rationality of thresholds.

variations within this interval. The robustness check for resetting the thresholds of comfort zone would be conducted later.

Compared with *TDEV* defined in Eq. (1), more commonly used indicators for energy related temperature change are HDD and CDD as we noted in Section 2. Daily data on temperature is needed for calculating HDD and CDD. However, it is not easily available for China to obtain temperature at the daily frequency. That is the reason why we use monthly data to calculate the deviation of temperature from comfort zone. Due to the same reason, Auffhammer (2014) also use monthly average temperature at provincial level to the empirical analysis.

Although *TDEV* might be a compromise indicator, we propose that it might be also reasonable and acceptable for this study. Using the same thresholds, the averaged HDD and CDD per day (if daily data is available) can be calculated as:

$$\begin{aligned} HDD_{ijt} &= \sum_{i=1}^{30}\left(18-temp_{ijt}\right)/30 \quad if \quad j\in\{Dec, Jan, Feb\} \\ CDD_{ijt} &= \sum_{i=1}^{30}\left(temp_{ijt}-27\right)/30 \quad if \quad j\in\{Jun, Jul, Aug\} \end{aligned} \tag{2}$$

The average temperatures in most provinces of China are higher than 27 °C in summer and lower than 18 °C in winter. In this case, when we only conduct analysis in summer and winter seasons, it is easy to obtain the following equations:

$$TDEV_{ijt} \approx \begin{cases} CDD_{ijt} & if \quad j\in\{Dec, Jan, Feb\} \\ HDD_{ijt} & if \quad j\in\{Jun, Jul, Aug\} \end{cases} \tag{3}$$

$TDEV_{ijt}$ would exactly equalize to HDD and CDD if monthly average temperatures in all provinces are higher than 27 °C in summer and lower than 18 °C in winter. By analyzing the dataset, we find that most of observations meet the requirement of exactly equalizing. Therefore, it is reasonable to employ *TDEV* as an indicator for energy related temperature change given the limitation of data availability.

After rationalize *TDEV*, we identify the intensive margin and extensive margin by two procedures. Residential electricity consumption (E) can be expressed as $E = AC \times \frac{E}{AC}$. The change of E can be decomposed as $\Delta E = AC \times \Delta\left(\frac{E}{AC}\right) + \Delta AC \times \left(\frac{E}{AC}\right)$, where AC is the number of air conditioners. The first term measures how usage pattern would affect electricity consumption, given current level of air conditioners (i.e., intensive margin in this paper). The second term measures how adoption decisions on air conditioners would affect electricity consumption (i.e., extensive margin in this paper). Through the decomposition, the changes of residential electricity consumption can be completely captured by intensive and extensive margins.

The empirical estimation is conducted as follows. The first step is to estimate how residential electricity consumption would be affected by temperature. It captures the aggregate effect of climate change, including intensive margin and extensive margin. Our basic model (BM) for electricity consumption is:

$$\ln\left(E_{ijt}\right) = \alpha_0 + \alpha_1 TDEV_{ijt} + \gamma \mathbf{X}_{1,ijt} + \mu_i + \varepsilon_{ijt} \tag{BM1}$$

where E_{ijt} is the residential electricity consumption in province i, month j and year t. ln is the symbol for natural logarithm. $\mathbf{X}_1$ is the matrix of control variable. μ_i here denotes a full set of province effects which capture heterogeneous shocks to provinces. Monthly-specific/year-specific effect are not included in the models. Due to meteorological shocks, temperatures in large geographical scale would also fluctuate every year. For example, China suffered from nationwide abnormal cold winter in 2008 which is commonly called "ice disaster"; temperature in the summer of 2014 was lower than that of 2013 (China Electricity Council, 2015). Thus, temperature might be an important common shocks to residential electricity consumption. Including time specific effect would filter the effects of temperature by including them into the effects of time specific common shocks.

The parameter α_1 measures whether and at what magnitude temperature variation has an effect on electricity consumption, regardless of intensive margin and extensive margin. For the empirical study in the first step, we have collected monthly data of electricity consumption and temperature for 30 provinces in China during 2009–2014, covering a wide range of climate zones.[4]

The regression above only enables us to look at the aggregate effects of climatic change on electricity consumption, but the intensive and extensive margins cannot be distinguished. In the second step, we estimate the influence of temperature on the purchasing decisions of air conditioners. Because the monthly data of air conditioners for each province are not available, the monthly temperature data have been merged into annual frequency:

$$YTDEV_{it} = \sum_{j=1}^{Mon} TDEV_{ijt} \tag{4}$$

where $YTDEV_{it}$ is the yearly deviation of temperature in province i and year t.

We conduct the following regression to estimate how climate change affects the stocks of air conditioners, i.e. extensive margin effect in basic model:

$$\ln\left(AC_{it}\right) = \beta_0 + \beta_1 YTDEV_{it} + \gamma \mathbf{X}_{2,it} + \mu_i + \eta_{it} \tag{BM2}$$

Excluding yearly deviation of temperature $YTDEV_{it}$, the other potential covariates are included in the matrix $\mathbf{X}_2$. The parameter β_1 measures how climate change affects purchasing decisions of households.

Particularly, through Eq. (BM2), air conditioner adoptions can be linked to residential electricity consumption. By affecting households' adoption decisions for air conditioners, 1 °C of temperature deviation would induce $100 \times \beta_1$ percent change of air conditioners. Recall that $\Delta E = AC \times \Delta\left(\frac{E}{AC}\right) + \Delta AC \times \left(\frac{E}{AC}\right)$, if we assuming that the usage pattern of air conditioners unchanged (i.e., $\Delta\left(\frac{E}{AC}\right) = 0$), electricity consumption would change $100 \times \beta_1$ percent (i.e., $\frac{\Delta E}{E} = \Delta AC \times \left(\frac{E}{AC}\right)/E = \frac{\Delta AC}{AC}$). Therefore, through Eq. (BM2), we can identify how much residential electricity consumption would be changed by temperature change through extensive margin.

The difference between α_1 and β_1 captures the change of usage pattern for given stocks of air conditioners, which is referred as intensive margin effect. In the next section, the basic model would be further extended to be more general for considering the seasonal and regional influences.

[4] Using total electricity consumption may include the contribution of the increased households. The effects of changed number of households would have been included into intensive effect. With this caveat in mind, the effects of increasing households might be just minor. The effect of changed households depends on how large the changes are. Meanwhile, the effect would be positive to intensive margin if the number of households increases, and be negative otherwise. Due to "one child policy" in the past decades, the growth rate of China's population has been very low (i.e., 1.3% in 2016). The number of households in recent years are thus quite stable as well. According to China's Statistical Year Book, it can be inferred that the total number of households in China was 423 million in 2009, and then increased to be 456 million in 2014, and then decreased to be 443 million in 2016. It can be concluded that the net effects of changed households might be very small, and would do not have substantial effects on our results. We thank the reviewer for pointing this out.

Table 1
Descriptive statistics.

Variable	Unit	N	Mean	Sd	Min	Medium	Max
E	10^4 kWh	1080	110,869.3	105,068.4	3377.0	90,028.5	944,080.2
Temperature	°C	1078	13.58	13.62	−21.10	17.80	32.60
TDEV	°C	1080	8.49	9.99	0	3.20	31.10
RI	Yuan/capita	1080	10,485.7	5813.1	3735.7	8741.0	34,521.3
EP	RMB/kWh	1080	0.753	0.102	0.500	0.770	0.930
AC	per 10^3 households	349	82.44	63.56	0.300	85.96	231.9
YTDEV	°C	360	49.95	23.39	3.00	46.10	110.90

4. Empirical results

4.1. Preliminary description and discussion for data

Besides the key variables, i.e., temperature, residential electricity consumption and stocks of air conditioners, residential income (denoted by "RI") and electricity price (denoted by "EP") are both included to examine how these factors affect residential energy consumption. It is well understood in the literature that income and electricity price are the main drivers of residential electricity consumption and air conditioner adoption. For example, in Auffhammer (2014)'s study on China's air conditioner adoption, he control for income level explicitly, while other possible drivers such as price of air conditioners, their efficiencies and the price of electricity are treated in fixed effect in panel data as unobservable confounders. However, the price of electricity is correlated with income in China and thus the coefficient on income would be biased if do not explicitly control for electricity price.[5]

Other widely considered factors, such as price of air conditioners and their efficiencies (Biddle, 2008), are not included for three reasons. First, we do not have provincial data on these variables. Second, these factors do not significantly correlated with either income or electricity, it can be treated through panel data estimated. Third, even one argues our assumption of uncorrelation, because whether is exogenous and random in most economic appliances, it acts like a "natural experiment" and thus in some settings allows researchers to identify statistically the causal effect of temperature on residential energy consumption and air conditioner adoption (Angrist and Krueger, 2001; Auffhammer et al., 2013).

Raw data employed in this paper are obtained from *China Premium Database*,[6] and all nominal variables have been deflated into constant price in 2000 year. Table 1 reports the descriptive statistics for these variables. It is slightly unbalanced due to several missing data for provincial temperature and air conditioners. As shown, temperature varies substantially among different provinces and different months, ranging from −21.1 °C to 32.6 °C. This provides substantial variation that enables us for understanding how people respond to climatic shocks.

It should be particularly pointed out that Eq. (1) implies that TDEV in monthly frequency consists of many zero-values in the dataset. Indeed, there are 346 zero TDEV observations out of 1080 in our dataset.[7] However, TDEV is used as a key explanatory variable, rather than dependent variable. In econometrics, large number of zero-values in dependent variable requires an appropriate treatment. Tobit model is usually applied in this case, such as studies in Li and Lin (2017). If zero-values appear in explanatory variable, they do not have adverse effects on either the consistency or the effectiveness of the parameter estimation. And thus, there is no need for special treatment for zero-values of TDEV.

The dataset is at provincial level. One might argue that household energy consumption respond might be different across whole province. There are two points we need to clarify. First, for a given province, the temperature variation within provinces might be much smaller than variation across provinces, because many provincial boundaries in China is historically determined by large mountains (such as Taihang mountain between Shanxi province and Hebei province) or large rivers (such as Yellow river between Shanxi province and Shaanxi province). These mountains and rivers are geographically segmentation for different provinces and makes temperature variation across provinces larger than variation within province. This provide some foundations to employ averaged data at provincial level. Second, even if household electricity consumption respond might be different across whole province, this does not matter for our estimation because what we obtain through the estimated coefficient is the averaged responses of households.

4.2. Basic results

Table 2 presents the results of how temperature affects residential electricity consumption, using 18 °C and 27 °C as thresholds. Column (1) is the most parsimonious specification, including only deviation of temperature from comfort zone, i.e., *TDEV*. Because residential electricity consumption has been taken natural logarithm, the estimate of 0.0039 implies that 1 °C deviating from comfort zone is typically associated with 0.39% higher electricity consumption in residential sector. In columns (2) and (3), we sequentially add income and electricity price into regression. The results show that income (electricity price) would stimulate (depress) residential electricity consumption, and significant

Table 2
Impacts on electricity consumption: results of basic and extended models.

	(1)	(2)	(3)	(4)
	ln(*E*)	ln(*E*)	ln(*E*)	ln(*E*)
TDEV	0.0039***	0.0036***	0.0036***	0.0904***
	(4.27)	(5.11)	(5.13)	(11.31)
ln(*RI*)		1.031***	1.128***	1.128***
		(25.99)	(19.77)	(20.84)
ln(*EP*)			−0.523**	−0.525**
			(−2.37)	(−2.51)
DumSW × *TDEV*				−0.0857***
				(−10.90)
Constant	11.22***	1.802***	0.757	0.722
	(991.62)	(4.97)	(1.33)	(1.34)
Hausman test	6.31**	8.08***	22.85***	24.22***
(*p*-Value)	(0.012)	(0.018)	(0.000)	(0.000)
N	1080	1080	1080	1080

Notes: *t* statistics in parentheses.
** $p < 0.05$.
*** $p < 0.01$.

[5] In China, the market-oriented reform is a gradual process, and this gradual process is particularly clear in price reform of factor market. Until recent years, the economic reform in energy market was not adequate. The prices of electricity are still artificially controlled or even determined by the Chinese government. The government usually sets a higher retail electricity price for provinces with higher income and lower retail price for lower income prices. According to the data published by *National Development and Reform Commission*, the first tier of retail electricity price is 0.617 Yuan per kWh in Shanghai (one of richest region in China), while that price in Yunnan (one of poorest region in China) is only 0.360 Yuan per kWh. As indicated in Auffhammer (2014), because of the positive correlation between electricity price with income level, the coefficient on income would be biased.

[6] China Premium Database provides detailed Chinese economic data. The web link of this database is: http://www.ceicdata.com/search_campaign.html?ui_lang=EN&how_hear=110&spage=11618#page=page-1.

[7] There is no zero-value for the yearly deviation of temperature.

at 5% level. The coefficients on *TDEV* do not change much, which are still around 0.4%.

TDEV measures deviation of temperature from comfort zone, while temperature is a meteorologically exogenous variable, at least in the short run. We further prove mathematically that the absence of correlation between *TDEV* and social/economic factors means that the estimated coefficient on *TDEV* would not be bothered much by omitted variable bias.

Assuming that the actual regression model is:

$$\ln\left(E_{ijt}\right) = \alpha_0 + \alpha_1 TDEV_{ijt} + \alpha_2 \mathbf{CV}_{ijt} + \gamma \mathbf{X}_{1,ijt} + \mu_i + \varepsilon_{ijt} \tag{5}$$

where, $\mathbf{CV}_{ijt}$ denotes exogenous factors that can affect residential electricity consumption, α_2 is the coefficient matrix. If actual regression equation excludes $\mathbf{CV}_{ijt}$, the corresponding estimator of α_1 is:

$$E(\tilde{\alpha_1}|TDEV, \mathbf{CV}) = \alpha_1 + \left(TDEV' \cdot TDEV\right)^{-1} \cdot TDEV' \cdot \mathbf{CV} \cdot \alpha_2$$

If these factors, **CV**, are not correlated with *TDEV*, i.e., $TDEV' \cdot \mathbf{CV} = 0$, excluding exogenous controllable variable **CV** would ***not*** lead to bias in the estimation of α_1. More details for the proof can be seen in Greene (2003). Because whether is exogenous and random in most economic applications, it acts like a "natural experiment" and thus allows researchers to identify statistically the causal effect of one variable on an economic outcome of interest (Angrist and Krueger, 2001; Auffhammer et al., 2013).

Similarly, *TDEV* does not correlate with income and electricity price, thus, the coefficients on *TDEV* have not changed much even including them into regression.

The response of residential electricity consumption to climatic impact might be different in summer and winter. For incorporating the asymmetry, we define a dummy variable, *DumSW*,which is equal to 1 for winter and 0 for summer. The specification of extended model (EM) for electricity consumption is as following:

$$\ln\left(E_{ijt}\right) = \alpha_0 + \alpha_1 TDEV_{ijt} + \alpha_2 DumSW_t \times TDEV_{ijt} + \gamma \mathbf{X}_{1,ijt} + \mu_i + \varepsilon_{ijt} \tag{EM}$$

The partial derivative of $\ln(E_{ijt})$ to temperature deviation is:

$$\partial \ln\left(E_{ijt}\right) / \partial\left(TDEV_{ijt}\right) = \frac{\partial E_{ijt}}{E_{ijt}} \Big/ \partial\left(TDEV_{ijt}\right) = \alpha_1 + \alpha_2 DumSW_t$$

Thus, $\partial \ln\left(E_{ijt}\right) / \partial\left(TDEV_{ijt}\right)$ is the semi-elasticity, implying that 1 °C increased temperature deviation to comfort zone would $100 \times (\alpha_1 + \alpha_2 DumSW_t)$ percent of electricity consumption in residential sector. For summer, the magnitude of climatic impact on electricity consumption is α_1 as $DumSW_t = 0$; while for winter, the magnitude is $\alpha_1 + \alpha_2$ as $DumSW_t = 1$. Accordingly, the coefficient of interaction term of $DumSW_t \times TDEV_{ijt}$, α_2, means that the asymmetric impacts of temperature.

The results are shown in the column (4) of Table 2. The coefficient on the cross term is significantly negative, confirming that the response of residential electricity consumption to climatic impact in winter is smaller than that in summer. In summer, 1 °C deviating from comfort zone is typically associated with 9.0% higher electricity consumption in residential sector. The magnitude is quite substantial. Meanwhile, the coefficient is only 0.5% (=0.0904–0.857) in winter. As we mentioned above, a half areas of China is covered by government-provided central heating system. Meanwhile, even in areas without central heating, the heating demand in wintertime is usually met by honeycomb coal and firewood especially in rural areas (Cai and Jiang, 2008), rather than electric appliances. Even for those households in the south that have equipped air conditioners, as far as we know, many households in the south only use air conditioners for cooling in summer. The building insulation performance is relatively poor in the south China. A majority of the buildings in the north have two-layer glass windows, and in some buildings, the air between the two glass layers is pumped out to prevent indoor heat from escaping. In contrast, most buildings in southern cities have single-glass windows that allow indoor heat to escape (Han, 2015). It makes heating expenditure using air conditioners more expensive because of lower heating efficiency. Therefore, the climatic impact on electricity consumption might be substantially asymmetric in summer and winter.

In order to distinguish intensive and extensive margin effects, we further estimate the effects of temperature change on the adoption of air conditioners. The results are presented in Table 3. Two points is worth noting: first, because data on air conditioners at provincial level are only available by annual frequency, the effects in summer and winter cannot be separated in this stage. Besides, just like capital stock, the stock of air conditioners can only be adjusted partially in a short run facing the shocks of temperature. The partial adjustments can be specified by a lagged term of air conditioners, AC_{t-1} (Li and Lin, 2016).

Column (1) in Table 3 shows a significant correlation between *YTDEV* and stocks of air conditioners, indicating that temperature deviating from comfort zone would induce households to purchase more air conditioners. More explicitly, 1 °C deviating from comfort zone leads to 0.5% increasing of air conditioners. After including income and electricity price in columns (2) and (3), the coefficients on *YTDEV* are still robust in both sign and magnitude. This is consistent with the finding in Auffhammer (2014) who finds that air conditioner adoption in China is sensitive to temperature, although they suggests a larger effect. This is not surprising because he adopts data only on China's urban regions, while rural regions are also included in our analysis.

Counterintuitively, the coefficient on electricity price is positive. This might be caused by the multicollinearity between income and electricity price, as the correlation between them is as large as 0.644. In column (4), both income and electricity price are added in regression, the coefficient on income becomes to be insignificant, suggesting that the partial effect of income and electricity price on air conditioners cannot be distinguished effectively. However, as we have proved for Table 2, due to the exogeneity of temperature, this does not bother the consistency of coefficient on *YTDEV*, which is still robust in column (4).

The question that needs to be answered is whether the estimated coefficients of *YTDEV* truly capture the impact of temperature change on air conditioners, rather than merely an coincidence. To mitigate this concern, falsification tests are performed by using other electric facilities that are not directly related to temperature. According to data availability, we use the washers, cameras, and cable telephones. The results for these appliances are reported in Table 4. For saving space, only

Table 3
Impacts on air conditioners purchasing: results of basic and extended models.

	(1)	(2)	(3)	(4)
	ln(*AC*)	ln(*AC*)	ln(*AC*)	ln(*AC*)
AC_{t-1}	0.721***	0.647***	0.653***	0.634***
	(29.25)	(18.64)	(15.66)	(14.99)
YTDEV	0.00490***	0.00449**	0.00449**	0.00441**
	(2.74)	(2.53)	(2.50)	(2.48)
ln(*EP*)		0.240***		0.213**
		(2.99)		(2.26)
ln(*RI*)			0.0940**	0.0296
			(2.02)	(0.54)
Constant	0.888***	1.280***	0.328	1.060**
	(7.63)	(7.35)	(1.09)	(2.41)
Hausman test	72.38***	74.52***	71.54***	73.36***
(*p*-Value)	(0.000)	(0.000)	(0.000)	(0.000)
N	317	317	317	317

Notes: *t* statistics in parentheses.
** $p < 0.05$.
*** $p < 0.01$.

Table 4
Falsification tests using other temperature-unrelated electric facilities.

	(1)	(2)	(3)
	Washers	Cameras	Cable telephones
YTDEV	0.00084	0.00064	−0.00155
	(1.07)	(0.43)	(−1.09)

Notes: *t* statistics in parentheses.

coefficients of temperature deviation are reported. Other coefficients not reported here are available upon request. As expected, none of these coefficients is statistically significant and magnitudes are very small, suggesting that estimated coefficients of *YTDEV* in Table 3 are not spurious relationships.

Therefore, summing up the results in Tables 2 and 3, one degree deviating from comfort zone increases residential electricity consumption by 0.5% in winter and 9.0% in summer. This finding is similar to Davis and Gertler (2015) which report large increases in electricity consumption on hot days with no offsetting from the reduced heating on cold days. Meanwhile, the households purchase about 0.4–0.5% more air conditioners with 1 °C of increased deviation to comfort zone, capturing the extensive margin effect of climatic impacts. The difference between these two results is the intensive margin effect. Given current level of air conditioners, electricity consumption increase with 1 °C deviation of temperature is up to 0.1% in winter and 8.5% in summer, and the results are quite robust to varying model specifications. As we have discussed, this is consistent with China's actual situation in winter of government-provided central heating in north areas and energy type choices in south areas for households that even have adopted air conditioners.

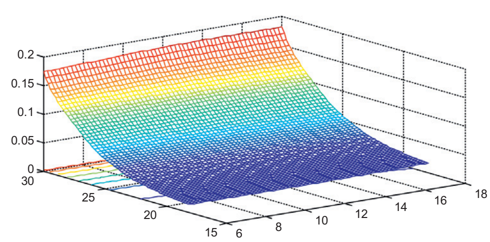
4.3. Robustness check for temperature thresholds

An implicit assumption for the above analysis is the thresholds for the comfort zone. We assume that people do not use air conditioners if the temperature is between 18 °C and 27 °C. In order to investigate whether the results would crucially depend on the setting of thresholds, we check the robustness of results under different thresholds. We want to check what the changes would be if we set different thresholds and whether our conclusions would be substantially altered.

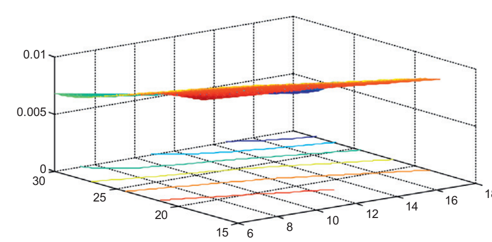
Previous literature that does not consider comfort zone usually employ 65 °F (18.3 °C) as the single threshold. Based on that:

(i) We choose 18 °C as the benchmark, and decline the lower threshold using 0.2 °C as an interval until 6 °C, i.e., 6 °C~18 °C. Similarly, the higher threshold is also increased using 0.2 °C as an interval until 30 °C, i.e., 18 °C~30 °C. There are 61 settings for lower and higher threshold each.
(ii) Applying the new combination of lower and higher thresholds, we re-calculate the deviation of temperature from comfort zone according to Eqs. (1) and (2).
(iii) We re-estimate the effects of climatic change on residential electricity consumption and on air conditioners.

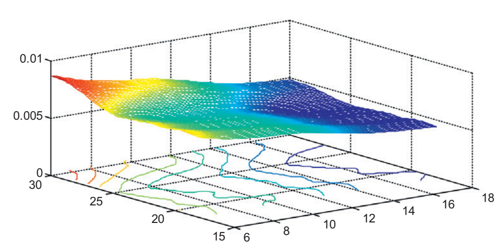
In total, the steps (ii) and (iii) needs to be repeated 3721 (61 × 61) times, and we could obtain estimates for α_1, α_2 and β_1 for each time. The results under different thresholds are displayed in Fig. 4.



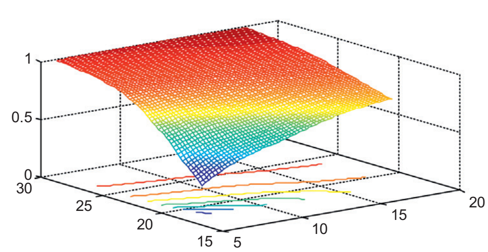
(a) effect on electricity consumption (summer)



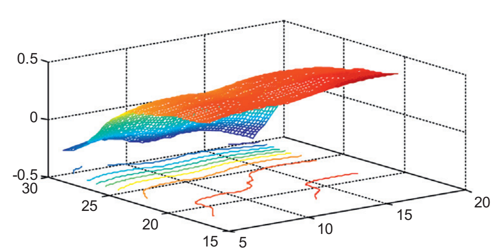
(b) effect on electricity consumption (winter)



(c) effect on stocks of air conditioners (extensive margin)



(d) proportion of intensive margin (summer)



(e) proportion of intensive margin (winter)

Fig. 4. The effects of temperature under different thresholds.

As can be observed, under all thresholds, larger temperature deviation from comfort zone is always associated with more residential electricity consumption and more air conditioners because the coefficients are always positive in Fig. 4(a)–(c). In comparison, the effects of temperature on residential electricity consumption is much larger in summer (Fig. 4(a)) than in winter (Fig. 4(b)), confirming the robustness of our results under different thresholds. On extensive margin, larger temperature deviation would always stimulate households to purchase more air conditioners, given the positive coefficients (Fig. 4(c)). This is consistent with the evidence presented by Deschênes and Greenstone (2011) showing that residential energy consumption responses are not specific to any climate model.

Fig. 4 also shows that, in summer, intensive margin accounts for the majority of total effect of temperature on residential electricity consumption in most cases (Fig. 4(d)), even near to 100% when the higher threshold of comfort zone is above 27 °C. It is straightforward that households are less inclined to purchase air conditioners if they are more adaptable to heat (for example, by constructing homes that can be well ventilated in summer). Contrarily, in winter, the proportions of intensive margin are always <50% (Fig. 4(e)). More extremely, when the higher threshold is larger than 27 °C, the intensive margin turns to be negative. A possible explanation might be that a household incline to purchase air conditioners that only use for cooling (rather than for both cooling and heating).[8] Thus, the electricity consumption per air conditioner (intensive margin) in winter would even decrease. It can be also inferred from the possible reasons here that in the long-term predictions for residential electricity consumption or the air conditioner adoption, as Auffhammer and Aroonruengsawat (2011) and Kahn (2016) point out, the potential impact of adaption strategies cannot be ignored.

In general, we can conclude from Fig. 4 that intensive margin plays a larger role on adjusting consumers' behaviors in summer by using more electricity; while its role is only minor in winter. These are also robust compared with the previous results in Subsection 4.1. The robustness reflects the current level of infrastructure (such as buildings) and adaption technologies, and thus the estimated parameters can be used to understand the complex relationship between temperature deviations and households' behaviors (Deschênes and Greenstone, 2011).

5. Further discussion

In a country as large as China, there are substantial differences in meteorology among different regions. Particularly, the areas of North China in winter are covered by government-provided central heating system; while the areas of South China are not. Thus, the effects of temperature change on residential electricity consumption and purchasing decisions of households might be heterogeneous between North and South China. In this section, we further discuss how the responses differ by climate zones.

In China, the areas with and without government-provided central heating are divided by Qin-Huai line. The North area of Qin-Huai line includes Xinjiang, Tibet, Qinghai, Gansu, Inner Mongolia, Shaanxi, Ningxia, Shanxi, Henan, Hebei, Shandong, Beijing, Tianjin, Liaoning, Jilin, Heilongjiang. These 16 provinces account for about a half of China's total territory. The other 15 provinces in mainland China are not covered by central heating in winter. In order to consider the heterogeneity in North and South, we define a dummy variable, *DumNS*, which is equal to 1 for North and 0 for South. Based on extended model above, our most general model (GM) is specified as following:

$$\ln\left(E_{ijt}\right) = \alpha_0 + \alpha_1 TDEV_{ijt} + \alpha_2 TDEV_{ijt} \times DumSW_t + \alpha_3 TDEV_{ijt} \times DumNS_i + \gamma \mathbf{X}_{1,ijt} + \mu_i + \varepsilon_{ijt} \tag{GM}$$

[8] For households in the north, they do not need to heat by air conditioners due to government-provided central heating. For households in the south, they usually do not heat by air conditioners due to large expenditure. As we have discussed, the reason is lower heating efficiency because of poor insulation performance in the south China.

Table 5
Climatic impacts on electricity consumption for each group based on GM.

	Summer ($DumSW = 0$)	Winter ($DumSW = 1$)
South ($DumNS = 0$)	α_1	$\alpha_1 + \alpha_2$
North ($DumNS = 1$)	$\alpha_1 + \alpha_3$	$\alpha_1 + \alpha_2 + \alpha_3$

By setting regional and seasonal dummies, the whole sample can be split into four groups: the north and south areas in winter and in summer. According to GM, the climatic impacts on residential electricity consumption for each group are shown in Table 5. It can be observed that the coefficient on cross term *DumNS* × *TDEV* (i.e., α_3) implies the impact difference between North and South China.

The estimated results are shown in the column (1) of Table 6. The coefficient on the cross term *DumNS* × *TDEV* is significantly negative, indicating that the effect of temperature change on residential electricity consumption is smaller in North China than in South China. This results is consistent with our expectation: in the North area of Qin-Huai line, households in winter do not need to react to temperature change by using more electricity for heating, because indoor temperature has been maintained within comfort zone by central heating system.

The above results are also supported by estimates using subsamples. Employing the sub-samples of North and South China, we re-estimate the regression. Columns (2) and (3) show the results of North and South China, respectively. It is very interesting that the effect of temperature change on electricity consumption is smaller in North China (6.8% in summer and 0.4% in winter) than in the south (10.4% in summer and 1% in winter). The North part of China is heated by government-provided central heating system in wintertime, thus electricity consumption is scarcely affected by temperature change. Again, even in the south, the responses of electricity consumption to climatic impact are smaller in winter because of expensive expenditure of using air conditioners for heating and choice of heating energy types.

In addition, we interest in whether the response of electricity consumption depends on the income of households. Thus, a cross term between *TDEV* and income has been added into regression. The results in column (4) suggests that the marginal effect of income is negative (−0.003 with *p*-value of 0.085). As expected, households with higher income have more choices to adapt to temperature changes than low-income households, such as by choosing houses with better insulation.

Table 6
Impacts on electricity consumption: results of general model by considering difference between North and South China.

	(1)	(2)	(3)	(4)
	ln(*E*)	ln(*E*)	ln(*E*)	ln(*E*)
TDEV	0.102***	0.0680**	0.104***	0.127***
	(11.53)	(2.41)	(11.86)	(7.48)
DumSW × *TDEV*	−0.0919***	−0.0641**	−0.094***	−0.091***
	(−11.34)	(−2.28)	(−11.66)	(−11.26)
DumNS × *TDEV*	−0.006***			−0.006***
	(−2.99)			(−3.01)
ln(*RI*)	1.127***	1.251***	0.901***	1.154***
	(20.91)	(17.80)	(10.61)	(20.58)
ln(*EP*)	−0.535**	−1.087***	0.309	−0.559***
	(−2.57)	(−3.76)	(1.00)	(−2.68)
ln(*RI*) × *TDEV*				−0.003*
				(−1.73)
Constant	0.714	−0.951	3.333***	0.461
	(1.33)	(−1.34)	(3.96)	(0.83)
Hausman test	24.58***	11.75***	8.05*	21.15***
(*p*-Value)	(0.000)	(0.019)	(0.090)	(0.001)
N	1080	540	540	1080

Notes: *t* statistics in parentheses.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

In a recent study of Atalla et al. (2017), they obtain similar finding using cross-country panel data.

In order to further investigate the difference of extensive margins in North and South China, we include the cross term of region dummy and yearly deviation of temperature, *DumNS* × *YTDEV*, into the regression of air conditioner adoption. The result is shown in column (1) of Table 7. The coefficient of cross term is 0.9% with a p-value of 0.107. It suggests that for air conditioner purchasing, households in North China respond a little larger than households in South China, though the difference can only be statistically significant at 15% level. To provide more confirmed evidence, we use the subsample of North and South China for the estimation, as shown in columns (2) and (3) respectively of Table 7. It shows that air conditioners would increase 0.55% in North China given 1 °C increase of temperature deviation, and the coefficient is significant at 5% level. In South China, however, the effect is only 0.14% and is statistically insignificant.

The results above reveal some interesting implications. Households in South China do not intend to purchase more air conditioners confronting temperature shocks. People living in lower latitude might be more adaptable to high temperature in summer (Albouy et al., 2016). While in winter, households in South China might be heated by Honeycomb coal, firewood (in rural areas) or other electric facilities, rather than air conditioners. For example, many households in Guizhou and Hunan provinces, including urban areas, choose electrothermal furnaces to heat their spaces. This would stimulate electricity consumption without any increase in air conditioners (although the increase in electricity consumption per temperature change is only 1% as shown in Table 6). On the other hand, for those who have owned air conditioners, they might just use existing air conditioners more frequently in summer rather than purchase more, given their more adaptability to high temperature in summer and other substitutable measures in winter. Thus, in South China, intensive margin dominates the aggregate effect of climatic change on electricity consumption.

On the contrary, households in North China might choose to purchase more air conditioners for two reasons. First, in summer, the highest temperature in North China is as high as that in South China. Take the year of 2013 as an example, the averaged highest temperature in provincial capitals was 38.28 °C in South China; while that in North China was 37.37 °C. Considering that people living in high latitude might be less adaptable to hot weather (Albouy et al., 2016), more air conditioners might be purchased. Fig. 5 displays the stocks of air conditioners per thousand households. As shown, households in North China purchased more air conditioners. Due to the government-provided central heating in winter, it is highly possible that air conditioners only use in summer.

Table 7
Impacts on air conditioner purchasing: results of general model by considering difference between North and South China.

	(1)	(2)	(3)
	ln(*AC*)	ln(*AC*)	ln(*AC*)
ln(AC_{t-1})	0.651***	0.505***	0.812***
	(15.64)	(8.46)	(14.55)
YTDEV	0.0023	0.0055**	0.0014
	(1.01)	(2.56)	(0.42)
DumNS × *YTDEV*	0.0095		
	(1.61)		
ln(*RI*)	0.096**	0.243***	−0.050
	(2.07)	(3.51)	(−0.84)
Constant	0.310	−0.871*	1.288***
	(1.04)	(−1.85)	(3.52)
Hausman test	73.53***	54.68***	22.05***
(p-Value)	(0.000)	(0.000)	(0.000)
N	317	158	159

Notes: t statistics in parentheses.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

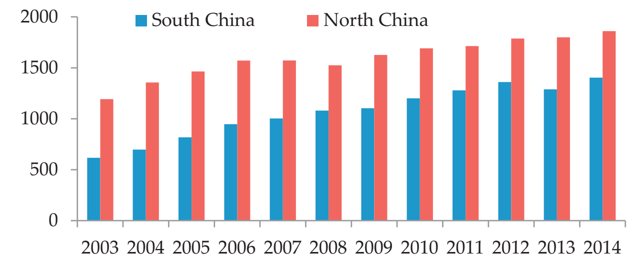


Fig. 5. The comparison of air conditioners in North and South China.

Recall that the coefficient of *DumNS* × *TDEV* in column (1) of Table 5 is negative, indicating that households in North China respond less regarding electricity consumption to climatic changes than those in South China. How could it coordinate with the larger propensity to adopt air conditioners in the north? It might be explained by the shorter duration of hot temperature in North China. Using 2013 as an example once again, the number of days that temperature is higher than 35 °C was 25 in South China and 9 in North China. The utility time of air conditioners might be much less in North China correspondingly, as people are inclined to turn off air conditioners on cooling days. Thus, more air conditioners in the north do not necessarily indicate larger electricity consumption. It can be inferred that extensive margin dominates the aggregate effect of climatic change on electricity consumption in the North areas.

Would the climatic impacts on residential electricity consumption and air conditioner adoption change over years? The answer to this question can help us evaluate the temporal dynamics of households' responses. For addressing this interesting question, we add the cross term of time and temperature deviation (*TDEV* for electricity consumption, and *YTDEV* for air conditioner adoption) into the regression. We estimate the preferred specification in Tables 2, 3, 6 and 7. The results of regression with time trend are shown in Table 8. What we particularly

Table 8
Regression with time trend.

	(1)	(2)	(3)	(4)
	ln(*E*)	ln(*AC*)	ln(*E*)	ln(*AC*)
TDEV	0.0898***		0.133***	
	(11.07)		(7.55)	
YTDEV		0.0033*		0.0014
		(1.66)		(0.61)
TDEV × *time*	0.0002		0.0005	
	(0.49)		(1.26)	
YTDEV × *time*		0.0001		0.0001
		(1.19)		(1.05)
DumSW × *TDEV*			−0.0060***	
			(−3.01)	
DumNS × *TDEV*	−0.0856***		−0.0910***	0.00890
	(−10.89)		(−11.23)	(1.51)
AC_{t-1}		0.624***		0.642***
		(14.50)		(15.13)
DumNS × *YTDEV*				
ln(*RI*)	1.111***	−0.0265	1.115***	0.0453
	(17.24)	(−0.37)	(17.39)	(0.68)
ln(*EP*)	−0.515**	0.212**	−0.538**	
	(−2.45)	(2.25)	(−2.57)	
ln(*income*) × *TDEV*			−0.0037**	
			(−2.09)	
Constant	0.882	1.606**	0.827	0.806
	(1.40)	(2.52)	(1.32)	(1.45)
Hausman test	25.30***	63.59***	20.93***	60.66***
(p-Value)	(0.000)	(0.000)	(0.001)	(0.000)
N	1080	317	1080	317

Notes: t statistics in parentheses.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

interested in is the coefficients of $TDEV \times time$ and $YTDEV \times time$. It shows that there are positive but not statistically significant change over time, no matter for the response to electricity consumption or air conditioner adoption. It is reasonable because the consuming habits and propensity are usually stable with time and would only change over a long period.

6. Conclusions

The global energy consumption has already raised many concerns for most countries, especially for China which is the largest energy consumer and CO_2 emitter worldwide. Due to the rapid process of urbanization in China, energy consumption in residential sector accounts for a substantial and increasing part of total energy consumption.

Residential sector is the only sector that directly relates to the households' behaviors regarding energy consumption. The main energy type consumed by residential sector is electricity, therefore, this paper conducts the estimates about the climatic impacts on electricity consumption in intensive and extensive margins for China. We use the random and exogenous temperature shocks to identify the effects of climatic change on household electricity consumption and on air conditioner adoptions. Based on the above results, the intensive and extensive margins can be separated, which identify the usage pattern and purchasing decisions of households for electric appliances. We specified seasonally specific temperature shocks by allowing different response functions of electricity consumption in summer and winter. The results are robust to thousands of pairs of thresholds in defining comfort zone. Furthermore, we investigate different responses of electricity consumption to temperature shocks by climate zone, especially considering government-provided central heating system in North China during wintertime.

It is meaningful to better understand the detailed relationships between temperature change and electricity consumption and using patterns in China. On the one hand, it can help us make informed decisions on planning future energy/electricity development, as well as climate and energy policies. On the other hand, it also provides knowledge and broader implications directed toward alleviating global climate warming. There are several novel findings and corresponding implications from this paper.

First, estimation results suggest that hotter summer or colder winter can result in significant increases in residential electricity consumption, particularly during the summer months. Global warming would result in decreased heating demand in winter and increased cooling demand in summer. Due to the larger temperature response in summer, given other conditions unchanged, global warming might encourage the overall electricity consumption in the whole year, and therefore, produce more greenhouse gas emissions because of China's coal-based electricity system. Especially, if other countries/regions also experience a China-like response, the positive feedback loop worldwide between climate and energy use might accelerate the speed of global warming.

Second, temperature response varies greatly across the climate zones in China. The effect of temperature change on residential electricity consumption is smaller in the north than in the south, no matter in summer or in winter. We infer that the regional difference might largely be induced by central heating system in North China in wintertime and the difference in the duration of hot temperature in summertime. This suggests a summer and winter electricity peak load in the South area of Qin-Huai line; while North area will only expect the peak load in summer because the North area of Qin-Huai line is equipped with government-provided central heating. It may have important consequences for electricity generation capacity, maintenance scheduling and electricity prices. For example, photovoltaic (PV) might be desirable to mitigate the impact of climate change by reducing the effects of peak load because it can match the diurnal demand for electricity (Borenstein, 2005).

Third, the intensive and extensive margins differ across seasons and climate zones, but there is no temporal dynamics over time. Across seasons, intensive margin in summer is larger than 50%, while in winter it is <50%. The results are quite robust to different model settings and varying temperature thresholds. Across climate zones, households in North China tend to purchase more air conditioners (larger extensive margin), but the utility time is less (intensive margin). The different temperature responses might be explained by people's difference in adaptability to hot weather and different duration of hot temperature across climate zones. This result can be extremely useful in managing the seasonal and regional electricity load, as well as projecting electricity generation capacity. The result suggests that the duration of peak load in North China might be short which occurred in summer, and thus how to handle it would be a challenge. Far beyond the expense of electricity generation, the availability of energy resources (such as natural gas) and the cost with regard to peak regulation would be high barriers to meeting the peak demand (McNeil and Letschert, 2008; Lin and Li, 2015). These barriers would in turn have significant economic and social consequences (e.g., increasing retail price of electricity, China's natural gas shortages in winter of 2017). Therefore, one could potentially foresee policy actions such as demand-side polices to manage the peak demand and more stringent energy efficiency targets for air conditioners.

Finally, it must be noted that, what we emphasize in this paper is that climate change is not the only one driver of electricity consumption and air conditioner adoption, but rather an important dimension that must be taken into account. Other factors, including income level and electricity price, must be considered simultaneously in future development of energy/electricity systems as well as for demand-side policies (such as time-of-use price).

Acknowledgements

We would like to express our sincere gratitude to the editor and anonymous referees for their insightful and constructive comments. The paper is supported by *National Natural Foundation of China* (Grant nos. 71703120, 71773028 and 71603079), *Social Science and Humanity Fund of the Ministry of Education* (No: 17YJC790068), *China Postdoctoral Science Foundation* (Grant nos. 2016M602784 and 2016M600772), *Special Foundation of China Postdoctoral Science* (No. 2017T100729), *Postdoctoral Science Foundation in Shaanxi Province* (Grant nos. 2017BSHTDZZ07 and 2017BSHYDZZ20), and the International Clean Energy Talents Program of ChinaScholarship Council (No. Liujinfa[2017] 5047).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2018.03.010.

References

Albouy, D., Graf, W., Kellogg, R., et al., 2016. Climate amenities, climate change, and American quality of life. J. Assoc. Environ. Resour. Econ. 3 (1), 205–246.

Amato, A.D., Ruth, M., Kirshen, P., et al., 2005. Regional energy demand responses to climate change: methodology and application to the commonwealth of Massachusetts. Clim. Chang. 71 (1), 175–201.

Angrist, J.D., Krueger, A.B., 2001. Instrumental variables and the search for identification: from supply and demand to natural experiments. J. Econ. Perspect. 15 (4), 69–85.

Asadoorian, M.O., Eckaus, R.S., Schlosser, C.A., 2008. Modeling climate feedbacks to electricity demand: the case of China. Energy Econ. 30 (4), 1577–1602.

Atalla, T., Bigerna, S., Bollino, C.A., 2017. Energy demand elasticities and weather worldwide. Econ. Polit. 1–31.

Auffhammer, M., 2014. Cooling China: the weather dependence of air conditioner adoption. Front. Econ. China 9 (1), 70–84.

Auffhammer, M., Aroonruengsawat, A., 2011. Simulating the impacts of climate change, prices and population on California's residential electricity consumption. Clim. Chang. 109 (1), 191–210.

Auffhammer, M., Mansur, E.T., 2014. Measuring climatic impacts on energy consumption: a review of the empirical literature. Energy Econ. 46, 522–530.

Auffhammer, M., Hsiang, S.M., Schlenker, W., et al., 2013. Using weather data and climate model output in economic analyses of climate change. Rev. Environ. Econ. Policy 7 (2), 181–198.
Besedeš, T., Prusa, T.J., 2011. The role of extensive and intensive margins and export growth. J. Dev. Econ. 96 (2), 371–379.
Bessec, M., Fouquau, J., 2008. The non-linear link between electricity consumption and temperature in Europe: a threshold panel approach. Energy Econ. 30 (5), 2705–2721.
Biddle, J., 2008. Explaining the spread of residential air conditioning, 1955–1980. Explor. Econ. Hist. 45 (4), 402–423.
Bin, S., Dowlatabadi, H., 2005. Consumer lifestyle approach to US energy use and the related CO_2 emissions. Energ Policy 33 (2), 197–208.
Borenstein, S., 2005. Valuing the Time-Varying Electricity Production of Solar Photovoltaic Cells. (Working Paper).
Burgess, R., Deschenes, O., Donaldson, D., et al., 2017. Weather and Death in India: Mechanisms and Implications of Climate Change. (Working Paper).
Cai, J., Jiang, Z., 2008. Changing of energy consumption patterns from rural households to urban households in China: an example from Shaanxi Province, China. Renew. Sust. Energ. Rev. 12 (6), 1667–1680.
China Electricity Council, 2015. Report on China's electricity demand and supply. (Available from). http://www.cec.org.cn/guihuayutongji/gongxufenxi/dianligongxufenxi/2015-03-30/135847.html (In Chinese, accessed at 2017 December 12).
Cho, S.H., Kim, H.J., Zaheeruddin, M., 2011. Revised heating degree days due to global warming for 15 major cities of South Korea. Build. Serv. Eng. Res. Technol. 32 (4), 377–383.
Considine, T.J., 2000. The impacts of weather variations on energy demand and carbon emissions. Resour. Energy Econ. 22 (4), 295–314.
Davis, L.W., Gertler, P.J., 2015. Contribution of air conditioning adoption to future energy use under global warming. Proc. Natl. Acad. Sci. 112 (19), 5962–5967.
De Cian, E., Lanzi, E., Roson, R., 2013. Seasonal temperature variations and energy demand: A panel cointegration analysis for climate change impact assessment. Climatic Change 116 (3-4), 805–825.
de Dear, R., Brager, G.S., 2001. The adaptive model of thermal comfort and energy conservation in the built environment. Int. J. Biometeorol. 45 (2), 100–108.
Deschênes, O., Greenstone, M., 2011. Climate change, mortality, and adaptation: evidence from annual fluctuations in weather in the US. Am. Econ. J. Appl. Econ. 3 (4), 152–185.
Dubin, J.A., McFadden, D.L., 1984. An econometric analysis of residential electric appliance holdings and consumption. Econometrica 345–362.
Fazeli, R., Ruth, M., Davidsdottir, B., 2016. Temperature response functions for residential energy demand–a review of models. Urban Clim. 15, 45–59.
Fikru, M.G., Gautier, L., 2015. The impact of weather variation on energy consumption in residential houses. Appl. Energy 144, 19–30.
Franco, G., Sanstad, A.H., 2008. Climate change and electricity demand in California. Clim. Chang. 87, 139–151.
Greene, W.H., 2003. Econometric Analysis. Pearson Education, India.
Gupta, E., 2012. Global warming and electricity demand in the rapidly growing city of Delhi: a semi-parametric variable coefficient approach. Energy Econ. 34 (5), 1407–1421.
Han, X., 2015. Central heating in south not a feasible idea. China Daily.
Hekkenberg, M., Benders, R.M.J., Moll, H.C., et al., 2009a. Indications for a changing electricity demand pattern: the temperature dependence of electricity demand in the Netherlands. Energ Policy 37 (4), 1542–1551.
Hekkenberg, M., Moll, H.C., Uiterkamp, A.J.M.S., 2009b. Dynamic temperature dependence patterns in future energy demand models in the context of climate change. Energy 34 (11), 1797–1806.
Henley, A., Peirson, J.D., 1997. Non-linearities in electricity demand and temperature: parametric versus non-parametric methods. Oxf. Bull. Econ. Stat. 59 (1), 149 (&).
Hsiang, S., 2016. Climate econometrics. Ann. Rev. Resour. Econ. 8, 43–75.
Javid, R.J., Nejat, A., Hayhoe, K., 2014. Selection of CO_2 mitigation strategies for road transportation in the United States using a multi-criteria approach. Renew. Sust. Energ. Rev. 38, 960–972.
Kahn, M.E., 2016. The climate change adaptation literature. Rev. Environ. Econ. Policy 10 (1), 166–178.
Kaufmann, R.K., Gopal, S., Tang, X., et al., 2013. Revisiting the weather effect on energy consumption: implications for the impact of climate change. Energ Policy 62, 1377–1384.
Lee, C.C., Chiu, Y.B., 2011. Electricity demand elasticities and temperature: evidence from panel smooth transition regression with instrumental variable approach. Energy Econ. 33 (5), 896–902.
Li, J., Lin, B., 2016. Inter-factor/inter-fuel substitution, carbon intensity, and energy-related CO_2 reduction: empirical evidence from China. Energy Econ. 56, 483–494.
Li, J., Lin, B., 2017. Does energy and CO_2 emissions performance of China benefit from regional integration? Energ Policy 101, 366–378.
Lin, B., Li, J., 2015. Analyzing cost of grid-connection of renewable energy development in China. Renew. Sust. Energ. Rev. 50, 1373–1382.
Mansur, E.T., Mendelsohn, R., Morrison, W., 2008. Climate change adaptation: a study of fuel choice and consumption in the US energy sector. J. Environ. Econ. Manag. 55 (2), 175–193.
McNeil, M.A., Letschert, V.E., 2008. Future Air Conditioning Energy Consumption in Developing Countries and What can Be Done About it: The Potential of Efficiency in the Residential Sector. Lawrence Berkeley National Laboratory.
McNeil, M.A., Letschert, V.E., 2010. Modeling diffusion of electrical appliances in the residential sector. Energy and Buildings 42 (6), 783–790.
Moral-Carcedo, J., Vicens-Otero, J., 2005. Modelling the non-linear response of Spanish electricity demand to temperature variations. Energy Econ. 27 (3), 477–494.
Pardo, A., Meneu, V., Valor, E., 2002. Temperature and seasonality influences on Spanish electricity load. Energy Econ. 24 (1), 55–70.
Petrick, S., Rehdanz, K., Tol, R.S.J., 2010. The Impact of Temperature Changes on Residential Energy Consumption. (Kiel Working Paper). (No. 1618).
Sailor, D.J., Pavlova, A.A., 2003. Air conditioning market saturation and long-term response of residential cooling energy demand to climate change. Energy 28 (9), 941–951.
Salari, M., Javid, R.J., 2016. Residential energy demand in the United States: analysis using static and dynamic approaches. Energ Policy 98, 637–649.
Song, Y., Sun, Y., Luo, S., et al., 2017. Indoor environment and adaptive thermal comfort models in residential buildings in Tianjin, China. Procedia Eng. 205, 1627–1634.
Wu, Y., Liu, H., Ni, Y., et al., 2015. Residents' thermal discomfort and adaptive responses of indoor environment in hot summer and cold winter zone, China. Proceedings of the 7th International Conference of SuDBE, Reading, UK, pp. 27–29.